There are FEW resources for human.
Crisis of Food Demands

- 805 million people: worldwide chronically undernourished
- 162 million chronically undernourished people are young children
- Central Africa and South Asia are experiencing the most hunger

Source: Global Hunger Index report, 2014
Crisis of Energy Demands

- Limited energy resources
- As petroleum resources are running out of, the renewable energy must be exploited.

Crisis of Water Demands

- Limited water resources
  - 40% of the world’s population lives in severe water-stressed areas;
  - by 2050, 2.3 billion more people than today.

Without the Sun, where can you get FEW?
Seawater
The origin of all creature
We may be from the sea.
WE can be from the sea.
Membrane
Water & Energy transport for all creature
Membrane

Water & Energy transport for all creatures
Technology
Technology should be green...

&

- FEW resources for human
- Sustainable
Green membrane technology to produce water & energy from seawater.
Membrane-based Desalination Technology in Water-Energy nexus Industry

Joon Ha Kim

Gwangju Institute of Science and Technology (GIST)
Outline

Water production
- MF
- UF
- NF
- RO
- MD
- MBR

Energy production
- Osmotic Potential
- PRO (Pressure Retarded Osmosis)
- RED (Reverse Electro-dialysis)

Driving Forces
- FO (Forward Osmosis)
- ED (Electro-dialysis)

Electro-chemical Potential

Salinity Gradient WE nexus processes
- RO
- PRO
- RED
Infrastructures...

- 4 main infrastructures:
  - Transportation, Telecommunication, Electricity, Water
- Investment rank (2011~2030):
  - Water > Electricity > Telecommunication > Transportation

Prospect of Worldwide Investment for Infrastructure

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>2001 to 2010 (annual average)</th>
<th>2011 to 2020 (annual average)</th>
<th>2021 to 2030 (annual average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads/Railways</td>
<td>269</td>
<td>299</td>
<td>350</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>654</td>
<td>646</td>
<td>171</td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td><strong>270</strong></td>
<td><strong>383</strong></td>
<td><strong>513</strong></td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td><strong>576</strong></td>
<td><strong>772</strong></td>
<td><strong>1,037</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,769</strong></td>
<td><strong>2,100</strong></td>
<td><strong>2,071</strong></td>
</tr>
</tbody>
</table>

(Unit: US$ billion)

Report from Organization for Economic Cooperation and Development (OECD, 2008)
Water & Energy production using membrane technology

Membrane Technology can be an alternative solution for Water & Energy problems at the same time, and for the need of co-generation infrastructure.
Membrane-based Desalination R&D Roadmap in Korea
(Korea Agency for Infrastructure Technology Advancement In the Ministry of Land, Infrastructure, and Transport, MoLIT)

Phase I
• SWRO : 2007-2014 [150 million USD]

Phase II
• MD-PRO : 2013-2018 [25 million USD]

Phase III
• Renewable energy hybrid w/ SWRO : 2016-2020 [TBD: approx. 30 million USD]
Outline

Water production
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Driven Forces
- FO (Forward Osmosis)
- Osmotic Potential

Electro-chemical Potential
- ED (Electro-dialysis)

Energy production
- PRO (Pressure Retarded Osmosis)
- RED (Reverse Electro-dialysis)

Salinity Gradient WE nexus processes
Osmotic Potentials

(RO, FO, & PRO)
Driving force: **Chemical potential (Osmosis)**

- Driven by chemical potential (Osmosis) difference
- Water passes through membrane

![Diagram showing water transport through a selective membrane](attachment:image.png)
Principle of Osmosis Membrane

Reverse Osmosis (RO)
- High pressure: $P > \Delta \pi$
- Irreversible Flow
- High Energy Consumption
- Semi-permeable Membranes

Forward Osmosis (FO)
- Water Flows by Natural Osmosis
- Separation
- Low Energy Consumption

Pressure-Retarded Osmosis (PRO)
- Low pressure: $P < \Delta \pi$
- Retardation
- Turbine
- Energy Generation
RO Membrane Technology becomes economically feasible.....

But, competition for reducing energy consumption just begins.
Features of seawater RO (SWRO) process

- Membrane material: cellulose acetate, polyamide
- Membrane module configuration: spiral wound type / hallow fiber type

### Advantages
- Lower energy consumption (3~4 kWh/m3) compared to distillation (10~16 kWh/m3)
- Well systematic process among the desalination processes
- Production of high quality freshwater (Na+ < 80~300 ppm)

### Disadvantages
- Membrane fouling
- Membrane cleaning/replacement
- Requirement of pretreatment system (MF, UF, DAF, DMF, and anti-scalant)
- Increase in cost to produce freshwater
Desalination and reuse rise to the challenge

Installed capacity by: technology

- RO
- MSF
- MED
- Hybrid
- ED

Saudi Arabia, USA, UAE, Australia, China, Kuwait, Israel, Libya, Spain, Algeria, India, Iran, Caribbean, Oman, Qatar

Source: Desalination Markets 2010
Future forecasts of SWRO desalination plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Today</th>
<th>Within 5 years</th>
<th>Within 20 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of water (2011 US$/m³)</td>
<td>0.5 ~ 0.8</td>
<td>0.4 ~ 0.6</td>
<td>0.2 ~ 0.4</td>
</tr>
<tr>
<td>Construction cost (US$/m³/day)</td>
<td>1,200 ~ 2,200</td>
<td>1,000 ~ 1,800</td>
<td>500 ~ 1,000</td>
</tr>
<tr>
<td>Power use of SWRO system (kWh/m³)</td>
<td>2.5 ~ 2.8</td>
<td>2.0 ~ 2.3</td>
<td>1.4 ~ 1.8</td>
</tr>
<tr>
<td>Membrane productivity (m³/day/SWRO membrane)</td>
<td>28 ~ 47</td>
<td>35 ~ 55</td>
<td>95 ~ 120</td>
</tr>
<tr>
<td>Membrane useful life (years)</td>
<td>5 ~ 7</td>
<td>7 ~ 10</td>
<td>10 ~ 15</td>
</tr>
<tr>
<td>Water recovery ratio (%)</td>
<td>45 ~ 50</td>
<td>50 ~ 55</td>
<td>55 ~ 65</td>
</tr>
</tbody>
</table>

Membrane 2-D modification → Still promising for next 20 yrs!

* Minimum theoretical energy for desalination at 50% recovery: 1 kWh/m³

* Practical limitations: No less than 1.5 kWh/m³

* Achievable goal: 1.5 – 2 kWh/m³

Ref: From Various Sources
Future technology of water treatment using membrane

**FORWARD OSMOSIS**
Water molecules migrate by natural osmosis, without energy input, into an even more concentrated “draw solution,” whose special salt (green) is then evaporated away by low-grade heat.
On the market: 2010-2012

**CARBON NANOTUBES**
An electric charge at the nanotube mouth repels positively charged salt ions. The uncharged water molecules slip through with little friction, reducing pumping pressure.
On the market: 2013-2015

**BIOMIMETICS**
Water molecules pass through channels made of aquaporins, proteins that efficiently conduct water in and out of living cells. A positive charge near each channel’s center repels salt.
On the market: 2013-2015
Principle of FO membrane process

Principle

- Naturally driven process without hydraulic pressure
- Run by chemical potential difference (i.e., concentration difference)
- Thermodynamically, reversible process

Advantages

- Low energy consumption
- Theoretically, No energy is required for membrane process

Limitations

- Lack of suitable membrane for FO
- Lack of appropriate draw solution
Features of FO process

- Naturally driven process by osmosis
- Theoretically, no energy is required for water production
- Contrary to RO, energy requirement is very low

Membrane process

- Water transports through membrane toward draw side
- Draw solution is diluted

Separation and recovery process

- Pure water is separated out from diluted draw solution
- Draw solution is recovered to be sent back into membrane process
Principle of PRO membrane process

(pressure-retarded osmosis)

- Chemical potential difference between feed and draw solution
- Depressurizing the permeate through hydro-turbine → Energy
Comparison of FO & PRO processes

<table>
<thead>
<tr>
<th>Similarity</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Two flows</strong> (feed solution, draw solution)</td>
<td><strong>Membrane orientation</strong></td>
</tr>
<tr>
<td>Utilization of osmotic pressure</td>
<td>FO : Draw solution recovery</td>
</tr>
<tr>
<td></td>
<td>PRO : Pressure exchanger</td>
</tr>
</tbody>
</table>
Features of PRO process

- **Two pre-treatments**
- **Energy recovery** for initial energy input

- **Concentration polarization (ICP, ECP), reverse draw salt flux**
- **Negative effect of coupling between ICP and reverse salt flux**

Future forecasts of PRO power plant

1MW PRO prototype plant
- Current: 5-6 kW
- Membrane area: 2000 m²

2MW PRO pilot plant
- Membrane area: 200,000-400,000 m²

25MW PRO Demo plant
- Membrane area: 5,000,000 m²

25MW PRO Commercial plant

Membrane Performance per m²

7.7 W/m²

11~12 W/m²

3 W/m²

Norway
Japan
Singapore
USA
Japan
Korea

2009 - 2011
2012 - 2015
2016 - 2019
2020 -
# Benefits of PRO power plant

## Challenging!

<table>
<thead>
<tr>
<th></th>
<th>PRO (Seawater)</th>
<th>PRO (Brine)</th>
<th>Solar Power</th>
<th>Wind Power</th>
<th>Waste Power</th>
<th>Fuel Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation cost ($/kWh)</td>
<td>0.21</td>
<td>0.16</td>
<td>0.86</td>
<td>0.19 – 0.28</td>
<td>0.13 – 0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Years of operation</td>
<td>17</td>
<td>17</td>
<td>20</td>
<td>17</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Utilization Factor</td>
<td>&gt;85</td>
<td>&gt;85</td>
<td>12</td>
<td>20</td>
<td>65</td>
<td>91</td>
</tr>
</tbody>
</table>

- Recoverable energy from ocean → **2,000 TWh** (IEAIOES, 2004)
  - ** provides energy to the **40 million household**
- Abundant marine resources → **sustainable**
- **No thermal pollution**
- **No CO₂ emission**

Ref) Akihiko Tanioka, “Power generation by PRO using concentrated brine from seawater desalination system and treated sewage; Review of experience with pilot plant in Japan”, 3\(^{rd}\) Osmosis Membrane Summit (2012)
PRO power plant applications

PRO applications 1
Open system

PRO applications 2
Underground system

Norman (1974)
Outline

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Driving Forces

- Osmotic Potential
  - FO (Forward Osmosis)
  - R O (Reverse Osmosis)

Electro-chemical Potential

- ED (Electro-dialysis)

Energy production

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Salinity Gradient

WE nexus processes

RO

PRO

RED
Electro-chemical Potentials
(ED & RED)
Principle of Electro-dialysis (ED)

- Voltage-driven membrane process
- **Electro-chemical potential difference** used to move salt through an ion-exchange membrane
- Styrene-Divinylbenzene copolymers

Ref. Desaldata.com, TheWaterTreatmentPlant.com
### Features of ED process

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Without phase change</td>
<td>• Not remove organic matter, colloids and SiO₂</td>
</tr>
<tr>
<td>• Relatively low energy consumption</td>
<td>• Only limited in low salinity (BWRO)</td>
</tr>
<tr>
<td>• Particularly suitable for separating non-ionized from ionized components</td>
<td>• Feed water pre-treatment is necessary</td>
</tr>
<tr>
<td>• Not affected by osmotic pressure</td>
<td>• Elaborate controls are required, the optimum operation can be difficult</td>
</tr>
<tr>
<td>• Lower O&amp;M cost</td>
<td>• Selection of materials of membrane is important to ensure compatibility with the feed stream</td>
</tr>
</tbody>
</table>
ED Applications

**REDUCE**
Electrolyte Content

- Potable water
- Food products
- Nitrate from drinking water
- Cooling tower water
- Boiler feed water
- Rinse water
- Effluent streams
- Sugar and molasses

**RECOVER**
Electrolyte Content

- Pure NaCl salt
- Al(l) salts
- Ni (ll)
- Zn (ll)
- Salts of organic acids
- Amino acids
- HCl

**Miscellaneous Applications**

- Salt splitting
- Metathesis
- Concentrate RO brines
- Ion substitution

......
Principle of RED process
(Reversed Electro-dialysis)

- Electro-chemical potential difference between brine and dilute → driving force
- Two membrane types: CEM and AEM
- Electrical current and the potential difference → Energy

Comparison of ED & RED

**Similarity**
- cation-exchange membrane (CEM) and anion-exchange membrane (AEM)

**Difference**
- ED: Electrolyte cell, one flow
- RED: Galvanic cell, two flows
Features of RED process

- Concentration polarization at membrane surface
- Not special RED membranes yet
- Possibility of membrane poisoning due to rinse solution

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Salinity Gradient WE *nexus* processes
SWRO hybridization with MD
Increase of product water

100 L Seawater Intake → Pretreat. → SWRO → Product water increase

50 L → Brine reuse

50 L + 30 L → MD

20 L → Denser Brine?
SWRO hybridization with MD & PRO
Increase of product water + energy

Seawater Intake → Pretreat. → SWRO → Fresh Water

Seawater → PRO 1 → PRO 2 → PRO 3 → Energy

Brine → MD → Denser Brine

River water? → Treated wastewater
Increase of product \textit{water + energy}

1. Sea water + Treated Wastewater
   \(0.5 \text{ mol/l}\) vs. \(0.01 \text{ mol/l}\)
   - 1.5 MJ

2. Brine + Treated Wastewater
   \(1.0 \text{ mol/l}\) vs. \(0.01 \text{ mol/l}\)
   - 3.0 MJ

3. Denser Brine + Treated Wastewater
   \(1.3 \text{ mol/l}\) vs. \(0.01 \text{ mol/l}\)
   - 4.2 MJ

**1 MJ**: the work generated by when 1 ton truck (160 km/h) hits a wall.

Fresh Water

Sea Intake

Pretreat.

Seawater

SWRO

Brine

MD

Denser Brine

PRO 1

Treated wastewater

PRO 2

PRO 3

Energy

River water?
Increase of product water + energy + green discharge

Seawater Intake → Pretreat. → SWRO → MD 1 → PRO 1 → PRO 2 → PRO 3 → MD 2 → Energy

Treated Wastewater → PRO 1 → PRO 2 → PRO 3 → Dilution

Fresh Water

Environment-friendly Discharge !!!
Seawater

Unlimited resource for WE , ,,
Technology should be green...

&

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- **Renewable energy hybrid w/ SWRO**: 2016-2020 [TBD: apprx. 30 million USD]
All **WE** may be from the sea.

Thanks for your attention!

Any question?